Pulsed Synchrotrons for Very Rapid Acceleration

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Abstract. When rapid acceleration is important, synchrotrons with very short pulse times can be used to accelerate particle beams. We will describe rapidly pulsed synchrotrons and their distinction from ordinary synchrotrons. We will introduce a hybrid synchrotron which interleaves pulsed magnets with superconducting dipoles to allow rapid acceleration while still maintaining a high average bending field. We will describe particular characteristics of the lattice design for these machines. We will describe how to design magnets to limit power consumption while still maintaining high fields. We will discuss the impact of the choice and properties of magnetic materials on the magnet performance. We show a magnet design that limits losses in the core while giving a high field by using multiple materials: 6.5% silicon steel for the back yoke due to its low losses at high frequencies, and 3% silicon steel in the pole for its high saturation field. The magnet has a unique coil configuration that minimizes eddy current losses. We compute losses and field quality for this design.

Keywords: pulsed hybrid synchrotron, magnet, muon accelerator, dipole
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INTRODUCTION

The synchrotron is a well-established machine for accelerating charged particles to high energies. The conventional synchrotron design maintains the magnet fields proportional to the beam momentum as the beam accelerates. This keeps the beam trajectory in the same location in the beam pipe throughout the acceleration cycle. The orbital period of the beam changes slightly as the beam energy increases and the RF frequency is adjusted to match this. The rate at which the beam accelerates is relatively modest (much longer than 1 ms), allowing sufficient time for RF frequency adjustment. The resulting modest ramp rate in the magnets limits the generation of eddy currents in the magnets and the beam pipe, leading to very small eddy current losses and negligible effects of eddy currents on the field quality.

Here we discuss pulsing a synchrotron much more rapidly with time scales of the order 1 ms. This is important for situations where one might want to accelerate very rapidly, such as when accelerating unstable particles (muons, for example) or for situations where high repetition rates are desirable (medical and and high power proton beams). At these ramp rates, there is a significant increase in losses in the magnets. Furthermore, eddy currents generated in the magnet and the beam pipe can create field errors. When we are accelerating this rapidly, we generally use high-frequency, high-Q cavities, in which case it is not practical to adjust the RF frequency during acceleration; thus the beam must be steered to make the orbital period of a reference particle constant throughout the acceleration cycle.

A high average bend field will keep the ring footprint small and use less RF. The field in the dipole magnets must be confined to iron outside the gap to keep the stored energy manageable; this limits the maximum bending field in the pulsed magnets to around 2 T. To achieve a high average bending field, one can interleave fixed-field superconducting dipoles with bipolar pulsed dipoles (first proposed by in 1996 by Summers [1]). We call this a hybrid synchrotron. The more frequently the dipoles are interleaved, the closer this machine behaves to a non-hybrid synchrotron. But inter-magnet spacing will reduce the average bend field available, and thus there is an optimum.

The remainder of this paper will first discuss some basic lattice design requirements and report some recent work on the lattice design. It will then describe magnet design requirements and some recent work on a dipole magnet design.

LATTICE

The hybrid synchrotron consists of a number of arcs with straight sections between them that contain RF cavities. The magnet fields increase continuously, while the energy increases only in the RF cavities. The energy will only be matched to the beam energy at the center of the arcs, while at the ends of the arcs, there will be some mismatch. There are two ways to address this latter issue. The first is to have short RF cavities in each cell (FODO, triplet, etc.). The difficulty with this solution is the synchro-betatron coupling this introduces. The second solution is to have arcs that

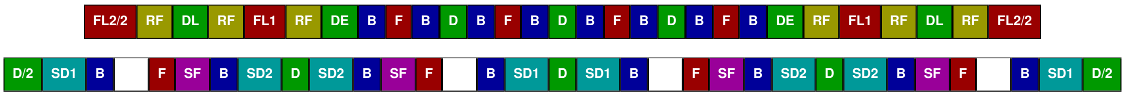

FIGURE 1. Lattice superperiod layout (top), with a detail of the arc (below) that includes sextupoles. The first letter describes the type of element: D for defocusing quadrupoles, F for focusing quadrupoles, B for dipoles (really interleaved pulsed and fixed superconducting dipoles), S for sextupoles, and RF for RF cavities. The D/2 at the ends of the arc detail is a portion of DE.

TABLE 1. Acceleration parameters for a muon collider.

Injection energy (GeV)	63	≈375	750	1500
Maximum circumference (km)	—	—	—	15
Ordinary/hybrid synchrotron	Ordinary	Hybrid	Hybrid	Hybrid
Normalized transverse emittance (μm)	25	25	25	25
Normalized longitudinal emittance (mm)	70	70	70	70
Minimum average acceleration rate (MeV/m)	3.5	3.5	3.5	—
Maximum emittance growth per stage (%)	3	3	3	3
Minimum amplitude transmitted (σ)	4	4	4	4

are first-order achromats, with the cavities in straight sections between these arcs. These arcs should be as compact as possible to have the maximum number of RF stations in the ring. We adopt the latter solution here.

In most applications, the closed orbit at the reference momentum (which is changing with time) of a fast pulsed hybrid synchrotrons should have a constant tune and orbital period (to keep the beam synchronized with the RF), a chromaticity that can be set to any value near zero (to control collective effects), and a position and dispersion of zero through the linac. Sufficient RF voltage should be installed to maintain the required average accelerating gradient, the RF bucket area should be sufficient for the longitudinal emittance, and the number of arcs should be sufficient to avoid transverse emittance growth. The aperture should be kept small to reduce the size of the pulsed magnet power supplies, losses in the magnets, and superconducting magnet costs. The synchrotron tune should be kept high to help control collective effects, which are a concern due to the high charge in the muon accelerator application.

Garren and Berg produced a lattice design in 2012 [2, 3] accelerating muons from 375 to 750 GeV. This lattice gave some idea of the required magnet apertures. The time of flight was not corrected in this lattice, nor was there any chromaticity correction. There were only 8 arcs in that lattice, which may lead to transverse emittance growth.

Arc sextupoles correct chromaticity for the full superperiod, and are arranged to eliminate second order geometric nonlinearities. The most compact arc cell accomplishing this has 4 FODO cells with a $\pi/2$ phase advance each. In addition, second order dispersion can be corrected. The layout for this cell is shown in Fig. 1. Quadrupoles on the arc ends are defocusing to minimize horizontal excursion in the dipoles. The straight section may be longer than what is shown in Fig. 1, but should have at least the families of quadrupoles shown to adjust the ring tune.

We are in the process of settling on lattice parameters for an acceleration chain for a muon collider, the high-level parameters for which are in Table 1. The longitudinal emittance growth limit places a strong constraint on the design. If an elliptical distribution filaments to match the constant-action curves of the RF bucket, the longitudinal emittance growth to lowest order for a Gaussian distribution is

$$\Delta\varepsilon_L = \frac{5}{24}\frac{\omega^4 T_1^3 V^2 \cos^2\phi}{\mu^2 \sin^3\mu} mc\varepsilon_L^2 \qquad\qquad 2\sin\frac{\mu}{2} = \sqrt{T_1 V \omega \sin\phi} \tag{1}$$

where, for each superperiod, V is the maximum energy gain in the RF, T_1 is the derivative of the time of flight with respect to beam energy, ϕ is the RF phase, ω is the angular RF frequency, ε_L is the normalized longitudinal emittance (in m), m is the particle mass, and c is the speed of light. We have had a first look at time of flight correction and how it relates to the arrangement of pulsed and superconducting dipoles in [4]. That time of flight correction will require the beam to move off-axis in the quadrupoles and sextupoles as the beam accelerates.

MAGNETS

To keep the machine footprint small, make efficient use of the RF cavities, and maximize the energy range of the machine, it is desirable to have a high field in the pulsed dipoles. Power losses in the magnets must be limited to

TABLE 2. Approximate resistivities and dipole fields achievable with a pole made from a number of different materials [5, 6, 7, 8]. Field values are based on first-pass magnet designs that have not been fully optimized.

Material	**Resistivity** $\mu\Omega$ **cm**	**Dipole field T**	**Material**	**Resistivity** $\mu\Omega$ **cm**	**Dipole field T**
Pure iron	10	1.75	6.5% Si steel	82	1.4
3.5% Si steel, non-oriented	40	1.75	Fe-Co (49% Fe, 49% Co, 2% V)	44	2.0
3.5% Si steel, grain oriented	50	1.8			

(a) **(b)**

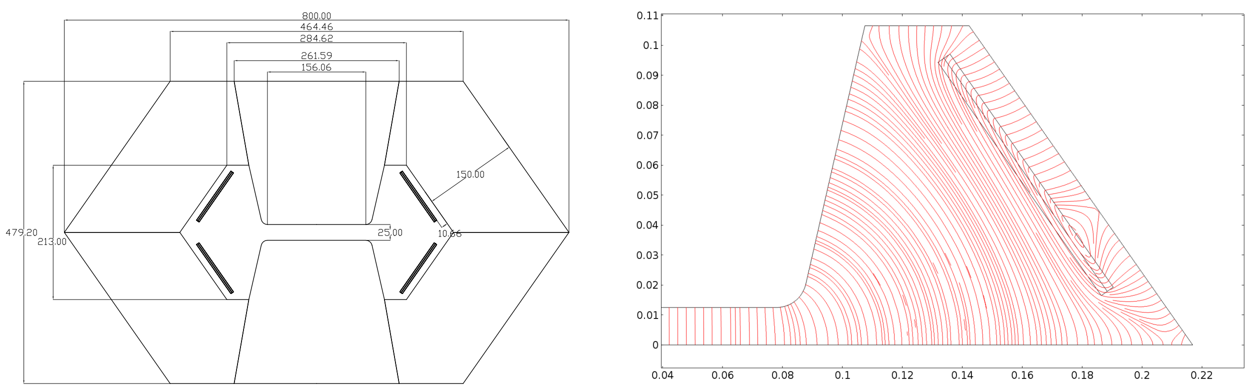

FIGURE 2. (a) Geometry of the magnet (dimensions in mm). (b) Field lines near the excitation coil at peak field.

avoid negating these benefits. The steel used for the magnet affects the losses in the magnet as well as the achievable field. As pulse times shorten, magnet losses increase, primarily because of eddy currents [9]. High steel resistivity is desired to reduce eddy current losses. The maximum field in a dipole from a given material depends both on the saturation magnetization and how the permeability of the material varies as the field in the iron increases. Table 2 gives representative values for the resistivity and an achievable dipole field for several types of steel.

The Fe-Co steel has the most attractive properties: a high maximum field and reasonable resistivity. The concern with using it in an accelerator, especially at high energy, is activation of the cobalt. 6.5% Si steel has a high resistivity, but suffers from low field magnitude. Grain oriented steel is also attractive with its relatively high field and reasonable resistivity. Summers built and tested magnets using grain oriented steel [10], showing that they could reach the desired fields at high pulsing rates. There are two difficulties with grain oriented steel, however. Since field lines are pinned along the grains, assembly and shape errors will propagate to the pole, creating field quality problems. Furthermore, existing simulation codes do not converge for anisotropic materials with nonlinear B-H curves, making it difficult to determine required tolerances. Pure iron achieves high fields as well, but has a low resistivity. Thus, 3.5% Si non-oriented steel is generally the best choice for these machines.

We propose a dual-material magnet design to simultaneously have low losses and a large dipole field. The back-yoke will use 100 µm thick 6.5% Si steel (JFE JNEX [8]) to give low losses in a region where high fields are not important, while the pole will use a different steel with a higher saturation field. In an earlier study [11] we used Fe-Co (VACOFLUX 48 [5]) for the pole, but in the results we describe here, we switch to 178 µm thick 3% Si non-oriented steel (Arnold Magnetics Arnon 5 [12]) due to the activation concerns. Thinner laminations of 3% SiFe (for example, 100 µm thick SURA NO10 from Surahammars Bruk, Sweden) do not show lower losses for 400 and 2500 Hz.

Recent work has focused on optimizing the geometry of the yoke and excitation coil to reduce power loss, resulting in the magnet geometry shown in Fig. 2 (a). The position of the excitation coil in the yoke was chosen so that the field lines are parallel to the surface of the current sheets (Fig. 2 (b)), which minimizes the losses. We utilize four bus bars, each with two current sheets that are 2.4 mm thick and 190 mm wide. The current sheets are isolated from each other using 40 µm thick Kapton^{TM} tape and positioned about 10 mm away from the yoke.

We simulate the magnet with the finite element package COMSOL Multiphysics (COMSOL AB, Tegnérgatan 23, SE-111 40 Stockholm, Sweden). The field quality and core losses are evaluated in 2D static non-linear simulations.

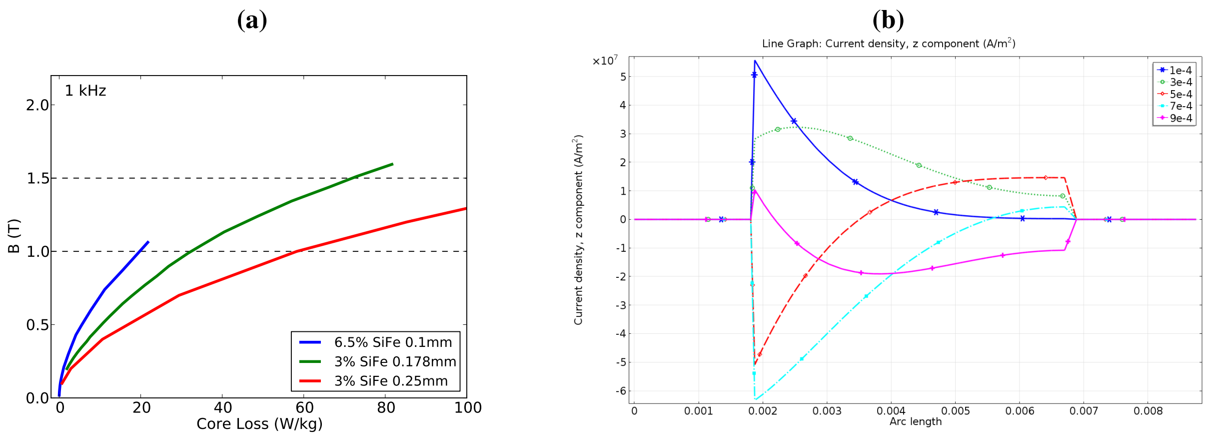

FIGURE 3. (a) Core losses of 6.5% SiFe and 3% SiFe (for two different thicknesses) at different fields for a frequency of 1 kHz. (b) Current density across the copper sheets of the excitation coil for different times.

TABLE 3. Dipole magnet specification

Total required dipole length	2200 m	Beam repetition rate	15 Hz
Gap	25 mm	Good field region (h x v)	60×10 mm^2
Design field B_{design}	1.5 T	Maximum field B_{max}	1.75 T
Field quality at B_{max}	1×10^{-3}	Ramp rate (equivalent frequency)	1000 Hz
Power Loss Yoke (at B_{design})	2.7 MW	Power Loss Coil (at B_{design})	0.55 MW
Total Power Loss (at B_{design})	3.25 MW	Stored energy (at B_{design})	4200 J/m
Current per bus bar	15600 A turns	Number of bus bars	4
Average peak current density cable	16 A/mm^2	DC resistance bus bar	1.77×10^{-5} Ω/m
Voltage required to drive current	866 V/m	Inductance	8.84 μH

The core losses are evaluated by a surface integration using the data from Fig. 3 (a). The losses in the excitation coil are evaluated in a 2D transient linear simulation, in which μ_r of the materials is chosen to be the lowest value obtained from the non-linear static simulations. We apply a sinusoidal voltage with a frequency of 1 kHz in the simulation. The voltage is adjusted until the desired current is reached. Fig. 3 (b) shows the current density across the copper sheets at different times; the figure shows the typical current distribution due to the eddy currents. Degradation of the field quality due to eddy currents in the laminations and hysteresis effects was studied earlier for a different design and found not to be a problem [13]. The temperature rise in the excitation coils is studied in a transient simulation assuming adiabatic heating, which is a worst case assumption. We assume the material properties of copper at room temperature.

As in [11], we consider the most challenging case, a dipole magnet for a hybrid synchrotron accelerating muons from 375 to 750 GeV. The dipole parameters are summarized in Table 3. Figure 4 (a) shows that the field quality meets requirements for fields as high as 1.75 T. The expected power loss for the entire ring is shown in Fig. 4 (b). Most of the power is dissipated in the pole (about 2 MW). The rest of the yoke dissipates about half as much power (1 MW) due to the use of 6.5% SiFe. The power loss in the excitation coil is only 500 kW. The temperature rise in the copper sheets is less than 0.2 K for 15 pulses. Cooling the yoke and excitation coils is straightforward; we envisage conduction cooling as outlined in [11].

SUMMARY

A pulsed hybrid synchrotron allows for very rapid acceleration of particles to high energies. Design work is continuing to find optimal solutions for muon acceleration. One of the greatest challenges for these machines are rapidly pulsed, high field magnets. We have shown that a window frame magnet can be optimized to minimize the power losses. The design utilizes two different materials in the yoke to accomplish a high dipole field in combination with low losses. With this approach a peak dipole field of 1.75 T appears achievable at the required field quality.

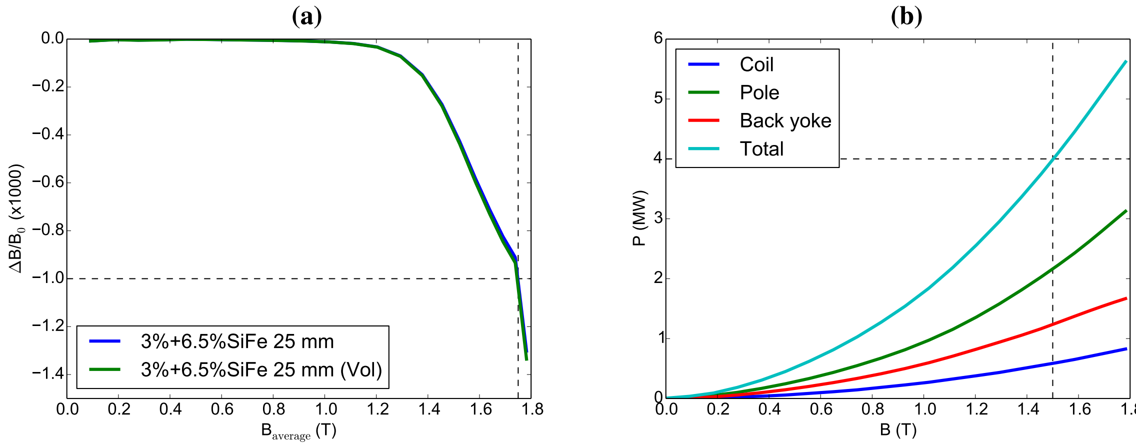

FIGURE 4. (a) Field quality as a function of peak dipole field. (b) Losses for 2200 m of pulsed dipoles.

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